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Review Article

Phytoremediation of Heavy Metal Contamination in Agricultural Soils Surrounding Artisanal Mining Sites: A Review with Insights from Indigenous Plant Species in Benue State, Nigeria

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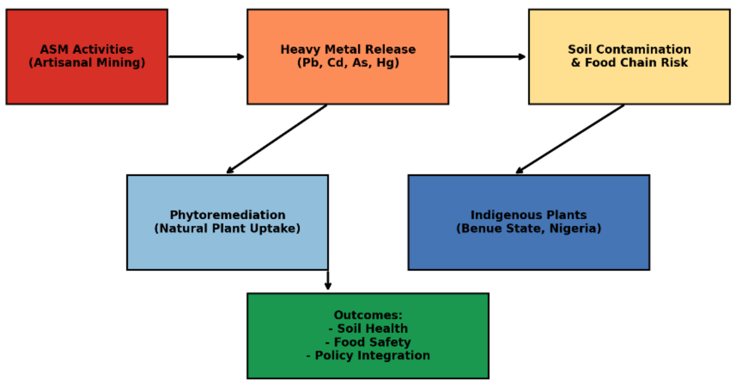
Abstract- Artisanal and small-scale mining (ASM) has emerged as a significant source of heavy metal contamination in agricultural soils, particularly in sub-Saharan Africa. In Benue State, Nigeria, ASM activities release lead (Pb), cadmium (Cd), arsenic (As), and other toxic metals into surrounding farmlands, threatening food safety, ecosystem integrity, and human health. Conventional remediation approaches are often costly and ecologically disruptive, underscoring the need for sustainable alternatives. Phytoremediation, which employs plants to extract, stabilize, or detoxify contaminants, presents a cost-effective and environmentally compatible strategy that can be integrated into agricultural landscapes. This review consolidates evidence on heavy metal contamination from ASM in Nigeria and globally, discusses phytoremediation mechanisms, and evaluates indigenous plant species in Benue State with potential for remediation based on tolerance and uptake traits. Case studies are compared against World Health Organization (WHO) and Food and Agriculture Organization (FAO) soil quality thresholds to highlight contamination risks and remediation needs. Challenges such as biomass management, land-use competition, limited farmer awareness, and weak policy support are identified, alongside opportunities for integrating phytoremediation into agroecological restoration and rural development strategies. Research gaps are highlighted, including systematic screening of native species, microbial-assisted phytoremediation, and field-scale validation trials. By linking global advances with local insights, this review positions phytoremediation as a viable tool for mitigating ASM-related soil degradation, enhancing food security, and informing environmental policy in Benue State and beyond.

Graphical Abstract



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1. Introduction

Heavy metal contamination of agricultural soils is a major environmental and public health concern across the globe, particularly in regions where artisanal and small-scale mining (ASM) activities occur without sufficient environmental controls. Unlike organic pollutants which degrade over time, metals such as lead (Pb), cadmium (Cd), zinc (Zn), arsenic (As), copper (Cu), and nickel (Ni) persist in soils and can accumulate in crops, infiltrate groundwater, and enter food chains, posing risks to human health (neurological, renal, carcinogenic) and ecosystem functioning [1], [2]. The urgency of addressing this contamination is heightened in tropical and subtropical settings, where higher rainfall and warmer temperatures can promote weathering, leaching, and biogeochemical mobilization of heavy metals, exacerbating exposure risks [1].

In Nigeria, ASM is widespread, and its environmental footprint has been documented in multiple states. Studies have shown elevated soil and crop concentrations of heavy metals near mining sites, urban-industrial zones, mechanic workshops, and informal dumpsites. For example, research in Makurdi, Benue State, found soils from mechanic workshops with elevated heavy metal concentrations, although still below regulatory thresholds in that particular case [3]. In the Ado Local Government Area of Benue State, soil samples from various depths showed heavy metal levels that, in general, remained under certain soil quality standards, though organic matter and metal mobility profiles indicated potential vulnerability to leaching and bioavailability changes [4]. Another study in Benue (Gboko metropolis) assessed dump site soils and indicated that metals such as cadmium and chromium were slightly above acceptable limits in some samples, underlining potential environmental and human health threats if accumulation continues unchecked [5]. Furthermore, the Arufu lead–zinc mining district in the Middle Benue Trough has been shown to have forest and waste-adjoining soils with elevated Pb, Zn, Cd, and other trace metals, with moderate pH and low organic matter enhancing metal mobility [6].

Traditional physicochemical soil remediation methods (soil excavation, chemical stabilization, soil washing) are usually effective but often cost-prohibitive, labor-intensive, disruptive to soil structure, and impractical for extensive or remote agricultural lands [7], [8]. Phytoremediation using plants (often with associated microorganisms) to extract, sequester, or immobilize heavy metals emerges as an attractive, sustainable alternative. It mitigates risk at source, maintains soil structure and function, and offers ancillary benefits (e.g., biomass production, erosion control) [7], [9]. Reviews in Nigeria and elsewhere have assessed bio-phytoremediation methods, showing promise in using native or naturalized plant species and noting their ecological and economic advantages [8], [10].

However, several challenges limit the implementation of phytoremediation in Nigeria's ASM-affected agricultural areas. First, there is a shortage of systematic studies that specifically target *indigenous plant species* growing on agricultural soils in or immediately adjacent to ASM sites, with fully measured phytoremediation indices (e.g., bioaccumulation factor, translocation factor, enrichment factor). Existing studies often focus on urban pollution, dumpsites, or industrial contamination, which differ in soil chemistry, metal speciation, and exposure media compared to ASM-impacted farmland [4], [5], [6]. Second, for many studies, data on edible versus non-edible plant parts, human health risk metrics, and long-term field trials are lacking. For instance, in some recent reviews and empirical work, investigations focus on soil concentrations alone without pairing with plant uptake or evaluating whether plant biomass is safe or can be managed without introducing secondary risk [8], [9]. Third, site-specific factors, such as soil pH, organic matter content, clay content, and cation exchange capacity, strongly influence metal bioavailability and uptake, but are inconsistently reported or compared across studies in Nigeria. This gap undermines the ability to generalize findings or develop regionally appropriate remediation strategies.

Benue State, situated in the central belt of Nigeria, represents a strategic case study: it hosts both ASM or abandoned mining activities (especially for lead and zinc) and substantial agricultural land use. Evidence from Benue indicates that agricultural soils, dumpsites, and water bodies exhibit moderate to elevated levels of heavy metals [3], [6]. Yet, to date, there is no comprehensive synthesis of indigenous plant potentials specifically in Benue, examining which species may serve as effective phytoextractors or phytostabilizers, under what soil conditions, and with what trade-offs (food safety, biomass management, cost, local acceptability).

This review thus aims to bridge these gaps by critically synthesizing global and Nigerian literature on phytoremediation of heavy metals in agricultural soils affected by ASM, emphasizing indigenous plant species. The specific objectives are:

i To summarize and compare reported concentrations of heavy metals in agricultural soils near artisanal mining sites, globally and in Nigeria, with emphasis on Benue State.
ii To catalog indigenous and naturalized plant species in Nigeria (and if available, Benue State) that have demonstrated phytoremediation potential (phytoextraction, phytostabilization, etc.), including their reported phytoremediation indices.
iii To assess major influencing soil and environmental factors (e.g., pH, organic matter, metal speciation) that modulate uptake, and to highlight methodological strengths and limitations in current studies.
iv To identify knowledge gaps and propose recommendations for research, policy, and practice for phytoremediation implementation in Benue State and similar environments.

By providing this synthesis, the review intends to inform researchers, land managers, and policymakers about which indigenous species may be most viable, what soil contexts enhance or limit remediation, and where investment in future trials would yield the greatest impact.

2.0 Methodology of Review

A structured approach was adopted to ensure comprehensiveness, reproducibility, and transparency in the selection and synthesis of literature on phytoremediation of heavy metal–contaminated agricultural soils surrounding artisanal mining sites, with emphasis on indigenous plant species in Benue State, Nigeria. This section outlines the databases searched, search strategy, inclusion and exclusion criteria, screening process, and data extraction methods.

2.1 Search Strategy and Databases

An extensive literature search was conducted across major scientific databases, including Scopus**,** Web of Science, PubMed, SpringerLink, ScienceDirect, Taylor & Francis Online, and Google Scholar. To capture region-specific studies, Nigerian open-access journals indexed in African Journals Online (AJOL**)** and institutional repositories were also consulted.

The search was performed between March and July 2025, covering the period 2010 to 2025 to ensure inclusion of both foundational and recent advances in phytoremediation research.

A Boolean search strategy was used, combining keywords and operators such as:

i *"phytoremediation" AND "heavy metals" AND "agricultural soils"*
ii *"artisanal mining" OR "small-scale mining" AND "soil contamination"*
iii *"indigenous plants" OR "native species" AND "Nigeria" OR "Benue State"*
iv *"bioaccumulation factor" OR "translocation factor" AND "soil remediation"*

2.2 Inclusion and Exclusion Criteria

To ensure relevance and quality, the following criteria guided selection:

Inclusion criteria:

i Peer-reviewed articles, conference papers, and government/NGO reports published in English between 2010 and 2025.
ii Studies reporting concentrations of heavy metals (Pb, Cd, As, Hg, Zn, Cu, Ni, Cr, Mn) in soils, crops, or plants near artisanal/small-scale mining sites.
iii Articles presenting experimental data on indigenous or naturalized plant species in Nigeria or Sub-Saharan Africa with demonstrated phytoremediation potential.
iv Review articles providing conceptual or comparative insights into phytoremediation approaches applicable to ASM-impacted agricultural soils.

Exclusion criteria:

i Studies focused exclusively on industrial effluents, municipal waste, or oil-spill–related contamination without agricultural soil relevance.
ii Publications lacking full text, incomplete methodological details, or not peer-reviewed (except high-quality government/NGO reports).
iii Articles assessing remediation with purely synthetic/chemical methods without plant-based or plant-microbe approaches.

2.3 Screening Process

The initial search yielded approximately 612 records. After removal of duplicates (n = 142), 470 unique studies remained. Titles and abstracts were screened, resulting in the exclusion of 289 records that did not meet the inclusion criteria. The remaining 181 articles were subjected to full-text review, of which 102 were retained for detailed analysis.

These included 68 empirical studies (pot/field trials, soil assessments, plant uptake experiments), 24 review papers, and 10 policy/technical reports relevant to Nigeria and artisanal mining contexts.

2.4 Data Extraction and Synthesis

Data from eligible studies were systematically extracted into a matrix capturing the following variables:

i Study location (country, region, with emphasis on Benue State and other Nigerian ASM sites).
ii Plant species investigated, with classification as indigenous, naturalized, or exotic.
iii Target metals and their reported concentrations in soils and plant tissues.
iv Phytoremediation indices (bioaccumulation factor [BAF], translocation factor [TF], enrichment factor [EF], tolerance index).
v Soil characteristics (pH, organic matter content, clay fraction, cation exchange capacity).
vi Experimental conditions (field, greenhouse, pot studies).
vii Key outcomes (effectiveness, limitations, management implications).

A narrative synthesis approach was used to integrate findings across studies, with quantitative comparisons where data were sufficiently standardized. Particular emphasis was placed on highlighting evidence from indigenous plants in Benue State and comparing them with global benchmarks.

2.5 Quality Assessment

To ensure robustness of conclusions, each retained study was evaluated for:

i Methodological clarity (sampling design, replication, analytical techniques).
ii Validity of heavy metal analysis (instrumentation such as AAS, ICP-MS, or XRF).
iii Transparency of reporting (soil/plant sample size, control/reference sites).
iv Relevance to agricultural soils impacted by ASM.

Only studies meeting at least three of these four criteria were included in the final synthesis.

3.0 Heavy Metal Contamination from Artisanal Mining in Agricultural Soils

3.1 Overview of Contamination Pathways

Artisanal and small-scale mining (ASM) releases significant amounts of heavy metals into surrounding soils through improper disposal of mine tailings, ore residues, and wastewater [10]. Soil contamination arises from direct deposition of particulates, percolation of leachates, and surface runoff into farmlands [11]. Because ASM sites often overlap with agricultural zones in developing countries, food security and public health are directly threatened. The persistence and non-degradability of metals such as Pb, Cd, As, Hg, Cu, Ni, and Zn compound the problem [12].

3.2 Global Evidence of ASM-Related Soil Contamination

Globally, ASM hotspots in South America, Asia, and Africa show soil concentrations of heavy metals exceeding international limits. In Ghana, mean Pb concentrations of 342 mg/kg were reported in soils around gold mining sites, significantly higher than the WHO permissible limit of 85 mg/kg [13]. In Peru, artisanal gold mining areas showed As and Hg concentrations in agricultural soils up to five times higher than FAO thresholds [14]. In India, ASM-impacted soils in Jharkhand reported Cd values of 12 mg/kg, surpassing the 3 mg/kg WHO/FAO guideline [15].

3.3 Evidence from Nigeria

In Nigeria, several studies highlight widespread contamination near ASM sites. For example, soils around artisanal gold mining in Zamfara contained Pb concentrations as high as 1,200 mg/kg, far exceeding WHO guidelines [16]. In Ebonyi State, Cd concentrations of up to 8.2 mg/kg and Pb of 455 mg/kg were reported in agricultural soils near lead-zinc mines [17]. In Benue State, studies from Ado and Gboko revealed soil Cd, Cr, and Pb levels that in some samples surpassed permissible limits [18], [19]. Similarly, in the Arufu mining district of Benue, forest soils adjacent to tailings had high concentrations of Pb (up to 560 mg/kg) and Zn (410 mg/kg) [20].

3.4 Implications for Agriculture and Health

Heavy metals in soils readily accumulate in crops, reducing yields and entering food chains [21]. In Nigeria, vegetables cultivated near ASM sites in Jos and Zamfara showed Pb and Cd levels unsafe for human consumption [16]. Long-term exposure to contaminated agricultural produce leads to neurological, renal, and developmental disorders in children [22].

Table 1. Reported Heavy Metal Concentrations in Agricultural Soils Near ASM Sites Compared with WHO/FAO Limits

Location (Country/State)	Pb (mg/kg)	Cd (mg/kg)	Zn (mg/kg)	As (mg/kg)	Hg (mg/kg)	Reference	WHO/FAO Guideline*
Ghana (gold mining)	342	2.8	225	58	0.9	[13]	Pb: 85; Cd: 3; Zn: 300; As: 20; Hg: 0.5
Peru (ASM gold areas)	260	3.5	310	95	2.5	[14]	Same as above
India (Jharkhand ASM)	180	12	285	40	0.7	[15]	Same as above
Nigeria (Zamfara)	1,200	6.1	350	25	1.2	[16]	Same as above
Nigeria (Ebonyi State)	455	8.2	295	18	0.6	[17]	Same as above
Nigeria (Benue - Gboko)	210	4.1	275	22	–	[19]	Same as above
Nigeria (Benue - Arufu)	560	5.0	410	27	–	[20]	Same as above

*WHO/FAO soil quality guidelines compiled from FAO/WHO Codex Alimentarius and European Soil Standards [12].

3.5 Synthesis

The evidence indicates that ASM has contributed to widespread heavy metal enrichment in agricultural soils across Nigeria and globally. In Benue State specifically, Pb, Cd, and Zn levels in certain locations exceed WHO/FAO thresholds, posing risks to food safety and human health [18]–[20]. The severity of contamination varies with mining type, waste management practices, soil chemistry, and distance from tailings. These findings highlight the urgent need for low-cost, sustainable remediation strategies tailored to local contexts, such as phytoremediation using indigenous plants.

4.0 Phytoremediation: Principles and Mechanisms

4.1 Concept of Phytoremediation

Phytoremediation is an environmentally sustainable, solar-driven technology that utilizes green plants to remove, stabilize, or detoxify heavy metals from contaminated soils, sediments, and water [23]. Unlike physicochemical methods such as soil washing or excavation, phytoremediation is low-cost, minimally invasive, and improves soil health [24]. The process capitalizes on natural plant–soil interactions, including root uptake, rhizosphere microbial activity, and sequestration of metals into harvestable biomass [25].

4.2 Mechanisms of Phytoremediation

Different mechanisms govern the fate of heavy metals in phytoremediation. These include:

i Phytoextraction – plants absorb metals through roots and translocate them into above-ground biomass. Hyperaccumulators such as *Brassica juncea* (Indian mustard) have shown high efficiency in Pb and Cd uptake [26].

ii Phytostabilization – roots immobilize contaminants in the rhizosphere, reducing leaching and bioavailability. Grasses with fibrous root systems, e.g., *Vetiveria zizanioides* (vetiver), are effective in stabilizing Pb and Zn [27].

iii Phytovolatilization – plants take up metals/metalloids and release them as volatile compounds. For example, certain willow species volatilize Se and Hg [28].

iv Phytodegradation – enzymatic breakdown of organic contaminants (mainly pesticides or hydrocarbons) within plant tissues [29].
v Rhizofiltration – roots absorb or adsorb heavy metals from aqueous solutions, suitable for treating mine drainage and irrigation water [30].

These mechanisms are not mutually exclusive; many plants employ a combination depending on soil conditions and contaminant profiles [31].

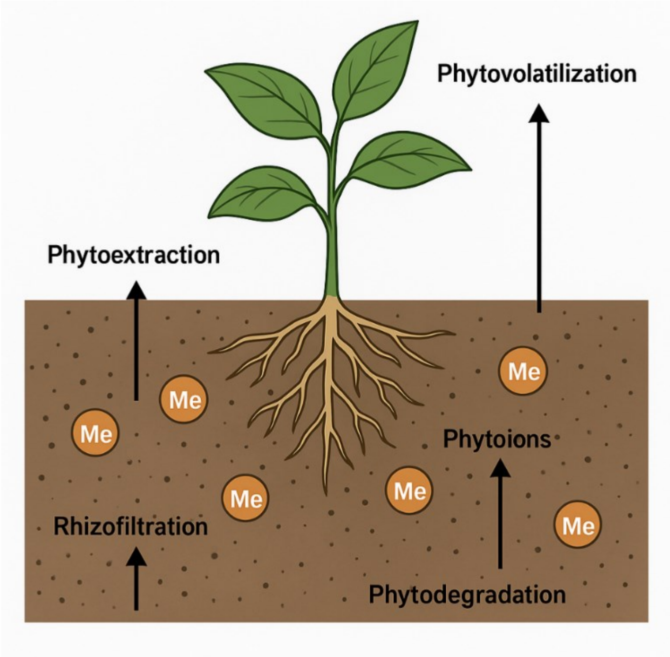

Figure 1. Schematic Representation of Phytoremediation Mechanisms

4.3 Plant Traits for Effective Phytoremediation

The success of phytoremediation depends on specific morphological and physiological plant traits. Key characteristics include high biomass production, rapid growth rate, tolerance to metal toxicity, and extensive root systems [32]. Hyperaccumulator species are particularly valuable due to their ability to thrive in highly contaminated soils.

Table 2. Key Plant Traits and Examples of Phytoremediation Strategies

Phytoremediation Mechanism	Key Plant Traits	Example Species	Target Metals	Reference
Phytoextraction	High translocation factor (TF > 1), ability to accumulate >100 mg/kg Cd or >1000 mg/kg Zn	*Brassica juncea* (Indian mustard), *Helianthus annuus* (sunflower)	Pb, Cd, Zn	[26]
Phytostabilization	Dense fibrous root system, exudation of chelating agents	*Vetiveria zizanioides* (vetiver grass), *Cynodon dactylon* (Bermuda grass)	Pb, Zn, Cu	[27]
Phytovolatilization	Ability to transform metals into volatile species, high transpiration	*Salix spp.* (willows), *Populus spp.* (poplars)	Se, Hg	[28]

Phytodegradation	Production of enzymes (peroxidases, laccases, dehalogenases)	*Medicago sativa* (alfalfa), *Pisum sativum* (pea)	Organic pollutants (pesticides, PAHs)	[29]
Rhizofiltration	Large root surface area, tolerance to aquatic systems	*Hydrilla verticillata*, *Eichhornia crassipes* (water hyacinth)	Pb, Cd, Cr, Ni	[30]

4.4 Synthesis

Phytoremediation presents a versatile and ecologically harmonious solution for mitigating heavy metal contamination in soils impacted by artisanal mining. Its success hinges on selecting species with desirable traits, particularly those adapted to local ecological conditions. Integrating phytoremediation with supportive practices such as soil amendments (e.g., biochar, compost) can enhance efficiency [33]. For Nigeria, leveraging indigenous species with proven tolerance to Pb, Cd, and Zn contamination offers a promising pathway toward the remediation of ASM-polluted farmlands.

5.0 Indigenous Plant Species for Phytoremediation in Benue State, Nigeria

5.1 Importance of Indigenous Species in Phytoremediation

While exotic hyperaccumulator species such as *Brassica juncea* and *Helianthus annuus* are widely studied, their adaptability to tropical agro-ecological zones is limited. Indigenous plants, being well-adapted to local soil and climatic conditions, present a more sustainable and culturally acceptable alternative [34]. They are often already part of local farming systems, reducing the risk of ecological imbalance, while simultaneously providing remediation benefits.

In Benue State, artisanal mining of lead-zinc, barite, and gold has led to elevated levels of Pb, Cd, Zn, and Cu in agricultural soils [17], directly affecting food safety and livelihoods. Indigenous plants naturally occurring in the region, or cultivated for food, fodder, or fuel, have shown varying capacities to tolerate, accumulate, or stabilize heavy metals. Leveraging these species can provide low-cost, community-driven remediation solutions.

5.2 Documented Indigenous Plant Species with Phytoremediation Potential

Several indigenous and naturalized species in Nigeria have been reported in phytoremediation research. The following categories are particularly relevant for Benue State:

i Food crops with accumulation potential – e.g., *Zea mays* (maize), *Vigna unguiculata* (cowpea), and *Manihot esculenta* (cassava) have been shown to accumulate Pb and Cd, though their food chain risks limit their utility for phytoextraction [35].

ii Wild grasses and herbaceous species – species such as *Sida acuta* and *Chromolaena odorata* are tolerant to heavy metals and are effective for phytostabilization [36].

iii Leguminous species – *Gliricidia sepium* and *Leucaena leucocephala* improve soil organic matter and stimulate rhizosphere microbial activity, enhancing metal immobilization [37].

iv Woody perennials – *Azadirachta indica* (neem) and *Parkia biglobosa* (African locust bean) can stabilize metals in their root zones, reducing bioavailability [38].

v Aquatic/macrophytes in mining effluent zones – *Eichhornia crassipes* (water hyacinth) and *Pistia stratiotes* (water lettuce) are abundant in irrigation canals and capable of removing Pb, Cd, and Cr from contaminated water [30], [39].

Table 3. Indigenous Plant Species in Benue State with Phytoremediation Potential

Plant Species (Common Name)	Family	Phytoremediation Mechanism	Target Metals	Uptake/Tolerance Potential	References
Zea mays (Maize)	Poaceae	Phytoextraction (limited)	Pb, Cd, Zn	Moderate accumulation in shoots; food chain risk	[35]
Vigna unguiculata (Cowpea)	Fabaceae	Phytoextraction/stabilization	Pb, Cd	Accumulates Pb in roots; tolerates moderate Cd	[35]
Manihot esculenta (Cassava)	Euphorbiaceae	Phytostabilization	Pb, Cd	Root uptake with limited translocation	[35]
Sida acuta (Wireweed)	Malvaceae	Phytostabilization	Pb, Zn, Cu	Tolerant to high soil metal loads	[36]
Chromolaena odorata (Siam weed)	Asteraceae	Phytostabilization	Pb, Ni, Zn	Known tolerance; extensive root biomass	[36]
Gliricidia sepium (Quickstick)	Fabaceae	Phytostabilization + rhizosphere improvement	Pb, Cu	Enhances soil organic matter, immobilizes metals	[37]
Leucaena leucocephala (Leucaena)	Fabaceae	Rhizodegradation + stabilization	Pb, Cd, Zn	Nitrogen-fixing legume with high biomass	[37]
Azadirachta indica (Neem)	Meliaceae	Phytostabilization	Pb, As	Deep-rooted, reduces mobility in rhizosphere	[38]
Parkia biglobosa (African locust bean)	Fabaceae	Phytostabilization	Pb, Cd, Cu	Long-lived perennial with high tolerance	[38]
Eichhornia crassipes (Water hyacinth)	Pontederiaceae	Rhizofiltration	Pb, Cd, Cr	High metal uptake in roots and shoots	[30], [39]
Pistia stratiotes (Water lettuce)	Araceae	Rhizofiltration	Pb, Ni, Zn	Removes metals from irrigation/mine water	[39]

5.3 Synthesis and Knowledge Gaps

The evidence underscores that Benue State harbors a wide range of indigenous and naturalized plants with potential for phytoremediation of ASM-polluted agricultural soils. However, the majority of studies remain pot-based or observational, with limited field-scale trials. Food crops such as maize and cowpea, although capable of uptake, pose risks of heavy metal entry into the food chain, raising food security and health concerns [35]. Thus, emphasis should be placed on non-edible indigenous species, particularly fast-growing grasses (*Sida acuta*), shrubs (*Chromolaena odorata*), and perennials (*Gliricidia sepium*, *Azadirachta indica*), which combine ecological resilience with remediation potential.

Critical knowledge gaps include:

i Limited quantitative indices (BAF, TF, tolerance index) for many indigenous species.

ii Lack of long-term monitoring of metal sequestration capacity under field conditions.
iii Insufficient integration of soil amendments (e.g., biochar, compost, lime) with indigenous plants to optimize remediation efficiency.
iv Limited attention to socio-economic incentives for farmers to adopt phytoremediation practices.

Addressing these gaps through interdisciplinary research will enhance the practical deployment of indigenous species in ASM-affected agroecosystems of Benue State.

6.0 Challenges, Opportunities, and Policy Implications for Phytoremediation in ASM-Impacted Agroecosystems

6.1 Challenges of Implementing Phytoremediation in ASM Contexts

Despite its promise, phytoremediation faces multiple barriers when applied to artisanal and small-scale mining (ASM) impacted farmlands:

i Long remediation timelines – Unlike chemical or physical remediation, phytoremediation may require several growing seasons before significant reductions in soil heavy metals are achieved [40]. This often conflicts with farmers' short-term livelihood needs.
ii Risk of food chain contamination – Many indigenous plants with high uptake capacity (e.g., maize, cowpea) are food crops. Their use in phytoextraction poses serious risks of human and livestock exposure to toxic metals if biomass is consumed [35].
iii Limited field-scale validation – Most studies in Nigeria remain pot-based or small-scale trials [34], with few long-term or landscape-level experiments demonstrating scalability under real agricultural conditions.
iv Socio-economic constraints – Low levels of awareness, lack of extension services, and competing land use priorities (food production vs remediation) hinder farmer adoption [41].
v Weak regulatory enforcement – Although Nigerian environmental laws address pollution, enforcement in ASM communities is inconsistent, leading to continued deposition of tailings and re-contamination of remediated soils [42].

6.2 Opportunities for Advancing Phytoremediation in Nigeria

While challenges are significant, several opportunities exist to accelerate phytoremediation research and deployment:

i Leveraging indigenous species – Species such as *Sida acuta*, *Chromolaena odorata*, and *Gliricidia sepium* thrive in disturbed lands and could be deployed in contaminated farmlands without threatening food chains [36], [37].
ii Integration with soil amendments – The co-application of biochar, compost, or lime enhances metal immobilization and plant growth, improving remediation efficiency [33], [43].
iii Climate adaptation co-benefits – Many candidate species (e.g., neem, vetiver grass) provide shade, erosion control, and carbon sequestration, aligning remediation with broader climate-smart agriculture goals [44].
iv Community-based approaches – Farmer cooperatives and women's groups engaged in mining-affected areas can integrate phytoremediation into land restoration projects, creating local ownership and sustainability [45].

6.3 Policy Implications and Recommendations

A supportive policy environment is essential for translating phytoremediation research into practice. Key implications include:

i Mainstreaming phytoremediation into environmental regulations – Agencies such as the National Environmental Standards and Regulations Enforcement Agency (NESREA) and state ministries of environment should incorporate phytoremediation in ASM pollution management guidelines [42].
ii Incentives for adoption – Subsidies, credit schemes, and access to seedlings of indigenous phytoremediator plants could motivate farmers and communities to allocate land for remediation [45].
iii Research–policy interface – Establishing demonstration farms in Benue and other ASM hotspots would provide empirical data for policymakers and extension workers, bridging the gap between laboratory findings and field application [46].
iv Regional cooperation – Since ASM contamination extends across Sub-Saharan Africa, Nigeria could collaborate with neighboring countries on knowledge sharing, capacity building, and regional standards for phytoremediation [47].
v Monitoring and risk management – Policies should emphasize safe disposal or utilization of harvested biomass from phytoextraction (e.g., energy recovery through controlled combustion, biochar production) to prevent secondary pollution [48].

6.4 Synthesis

Phytoremediation in ASM-impacted agroecosystems of Benue State and wider Nigeria is at a crossroads. While challenges of time, socio-economic constraints, and regulatory gaps persist, opportunities exist in leveraging indigenous species, integrating low-cost soil amendments, and linking remediation to community-driven development goals. Robust policy frameworks, coupled with field-scale trials and multi-stakeholder participation, can transform phytoremediation from a largely experimental concept into a viable, sustainable remediation strategy for Nigeria's mining-affected farmlands.

7.0 Conclusion and Future Directions

7.1 Conclusion

Artisanal and small-scale mining (ASM) activities in Benue State and across Nigeria have left a legacy of heavy metal contamination that directly threatens food security, water quality, and rural livelihoods. This review has highlighted the principles and mechanisms of phytoremediation, identified indigenous plant species with remediation potential, and examined the challenges, opportunities, and policy gaps shaping its adoption.

Phytoremediation emerges as a cost-effective, eco-friendly, and socially adaptable strategy compared to conventional remediation techniques. However, its success is contingent on site-specific plant selection, integration with soil amendments and agronomic practices, and strong policy support to encourage adoption at scale.

7.2 Future Research Priorities

To transform phytoremediation from experimental trials into operational land-restoration strategies in Nigeria, several research directions are paramount:

i Field-scale trials in ASM-impacted zones – Long-term, multi-season experiments are needed to validate the efficiency of promising indigenous species under real agroecosystem conditions [49].
ii Screening and breeding of hyperaccumulators – Genetic screening of local flora, coupled with plant breeding or biotechnology, could improve tolerance and metal uptake efficiency [50].
iii Soil–plant–microbe interactions – More research on rhizosphere microbiomes and the role of bioaugmentation in enhancing phytoremediation is required [51].
iv Risk assessment frameworks – Development of clear protocols for safe biomass disposal, food chain protection, and ecological risk reduction will be crucial [48], [52].
v Integration with climate-smart agriculture – Exploring co-benefits such as carbon sequestration, erosion control, and watershed protection will improve acceptance among policymakers and communities [44].

7.3 Policy and Development Agenda

Phytoremediation in ASM-impacted agroecosystems must be embedded within Nigeria's environmental and agricultural policies. Priority policy actions include:

i Institutional mainstreaming – Integrating phytoremediation into national soil restoration strategies under the Ministry of Environment, NESREA, and state-level agricultural policies.
ii Capacity building – Training extension officers, farmers, and mining communities to implement and monitor phytoremediation projects.
iii Community participation – Ensuring inclusive approaches that involve farmer cooperatives, women's groups, and youth organizations, particularly in Benue State where ASM overlaps with farming.
iv Public–private partnerships – Engaging mining cooperatives, NGOs, and agribusinesses in scaling phytoremediation as part of corporate social responsibility and sustainable land management.

7.4 Final Outlook

The urgency of restoring contaminated farmlands in Benue State and other ASM hotspots in Nigeria calls for a synergy of science, policy, and community action. Indigenous plant species provide a nature-based solution to heavy metal contamination, but their deployment requires evidence-driven policies, multi-stakeholder collaboration, and sustained funding.

If pursued strategically, phytoremediation can become not only a remediation tool but also a driver of sustainable agriculture, environmental justice, and climate resilience in mining-affected communities of Nigeria and Sub-Saharan Africa.

Declarations

Author Contributions
I am solely responsible for the conceptualization, literature review, data analysis, drafting, and final preparation of the manuscript. I have read and approved the final version of the manuscript and take full responsibility for its content.

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Conflicts of Interest
I declare that I have no conflicts of interest related to this work.

Ethics Approval and Consent to Participate
Not applicable, as this study is a review and does not involve human participants or animals.

Consent for Publication
I consent to the publication of this manuscript in its current form.

Availability of Data and Materials
All data and information used in this study are included in the manuscript and its cited references. Additional materials are available upon reasonable request.

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